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TECHNICAL REPORT ARCCB-TR-93035

ISOTHERMAL BAINITE PROCESSING OF ASTM A723 COMPONENTS

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SEPTEMBER 1993

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REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE September 1993	3. REPORT TYPE AND DATES COVERED Final

4. TITLE AND SUBTITLE ISOTHERMAL BAINITE PROCESSING OF ASTM A723 COMPONENTS	5. FUNDING NUMBERS AMCMS: 6111.02.H611.1
6. AUTHOR(S) P.J. Cote, R. Farrara, T. Hickey, and S.K. Pan	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Benét Laboratories, SMCAR-CCB-TL Watervliet, NY 12189-4050	8. PERFORMING ORGANIZATION REPORT NUMBER ARCCB-TR-93035
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army ARDEC Close Combat Armaments Center Picatinny Arsenal, NJ 07806-5000	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Standard quench procedures can generate quench cracking problems in components with complex shapes and surface irregularities such as muzzle brake castings. An attractive alternative is isothermal bainite processing which, in principle, can avoid transformation stresses. The disadvantage of this process is the generally inferior ductile-brittle transition temperature of bainite relative to martensite. In recent studies, we found that isothermal bainite forms *below* the martensite-start temperature in ASTM A723. The properties of this low temperature form of bainite are found to match those of standard quenched and tempered martensite in contrast to the higher temperature forms of bainite. The present report describes successful attempts at isothermal bainite processing of large scale components using molten salt baths.

14. SUBJECT TERMS Isothermal Bainite, ASTM A723, Molten Salt Processing, Heat Treatment	15. NUMBER OF PAGES 12
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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ACKNOWLEDGMENTS

The authors would like to express their thanks to Charles Morse of the Watervliet Arsenal Heat Treating Shop for assisting in the isothermal process and performing the final tempering; to Allen Gageway of Operations Directorate (Watervliet Arsenal) for preparing the mechanical test specimens; and to the late Daniel Fusco and Daniel Corrigan of Benét Laboratories for the mechanical tests.

INTRODUCTION

Isothermal processing of steel in the present context refers to isothermal transformation of the high temperature austenite phase to the bainite microstructure. The main advantage of isothermal processing over the standard quench process to form martensite is that the transformation to bainite is slow and, in principle, can proceed uniformly throughout the volume of the component so that the resulting residual (transformation) stresses are small. In the past, bainite has been avoided because the high ductile-to-brittle transition temperature of the familiar bainite microstructures formed above the martensite start temperature, M_s. The current focus is on bainite microstructures formed *below* M_s. It was shown (refs 1,2) that duplex microstructures of martensite and isothermal bainite formed below M_s exhibit properties that match or exceed those of tempered martensite. These earlier studies utilized laboratory size specimens weighing several pounds or less so that the cooling path is easily controlled. The concern addressed in the present study relates to components weighing hundreds of pounds (e.g., muzzle brakes) and whether sufficiently high cooling rates could be achieved in a molten salt bath that is maintained in the 392° to 482°F (200° to 250°C) range to bypass formation of the deleterious bainite above M_s.

Earlier work (ref 3) on ASTM A723 showed the dramatically higher hardenabilities of the 3 percent nickel compositions over the 2 percent compositions. Given the inherently lower cooling power of the elevated temperature molten salt quench bath, it was expected that the high nickel compositions would be needed to avoid the deleterious bainite that can form during cooling from the (molten salt) austenitization bath.

The present experiment used three 100-pound cylinders cut from the breech end of gun tubes. Molten salt baths were used for austenitization and for the cooling/isothermal processing. The results confirmed the expectation that high nickel compositions are better for isothermal molten salt processing of large masses. The more significant result is that properties comparable to standard quench and temper results are obtained with the quench bath set at 482°F.

EXPERIMENTAL

Three ASTM A723 cylinders weighing approximately 100 pounds each were used in the present study. Two were from the breech end of 120-mm tubes with a nickel content of 3 percent, and the other was from a breech end of a 155-mm tube with a nickel content of 2 percent. Molten salt thermal processing was conducted in the Watervliet Arsenal (Watervliet, NY) heat treatment facility. The cylinders were immersed in the austenitization bath for one hour at 1550°F; the cooling and one-hour isothermal hold were accomplished by removal of the cylinders from the austenitization bath and immediate immersion into the stirred, temperature-controlled cooling bath maintained at either 392° or 482°F. A chromel-alumel thermocouple probe was mounted into threaded holes in the cylinders for two of the runs to determine the actual cooling paths for the cylinders. The 155-mm cylinder was furnace-tempered at 1100°F, while the 120-mm cylinders were tempered at 1125°F for one hour after the molten salt processing to obtain the optimum strength and toughness of the mixed martensite and low temperature bainite microstructure. The cylinders were then machined to provide midwall, transverse tensile, and Charpy specimens for mechanical properties.

RESULTS

Table 1 gives the compositions of the three cylinders used in the present experiment. Specimen 1 is the 155-mm cylinder isothermally processed at 482°F, specimen 2 is the 120-mm cylinder isothermally processed at 482°F, and specimen 3 is the 120-mm cylinder isothermally processed at 392°F. The main difference is the nickel content.

Table 1. Compositions of Cylinders Used in Molten Salt Isothermal Processing Study
(Listed as weight percentages)

	Specimen		
	1	2	3
Nickel	2.03	3.00	2.97
Carbon	0.36	0.34	0.33
Manganese	0.52	0.61	0.62
Phosphorus	0.011	0.013	0.014
Sulfur	0.007	0.006	0.003
Silicon	0.17	0.17	0.18
Copper	0.09	0.10	0.09
Chromium	0.90	1.01	1.03
Vanadium	0.10	0.10	0.10
Molybdenum	0.45	0.45	0.46

Figure 1 is a photograph of typical cylinders used in this study. The two on the ends are from 155-mm tubes and the center block is from a 120-mm tube. The threaded holes located midwall were drilled midway into the cylinders to insert the thermocouple.

Figure 2 shows the continuous cooling transformation (CCT) diagram obtained by thermal and magnetic analyses for the high nickel (~3 percent) ASTM A723 steel. The bainite knee for the 2 percent nickel is shifted to shorter times by roughly a factor of ten (ref 3). The dotted line indicates the standard quench path that generates high residual stresses. The dashed line is an idealized cooling path that bypasses the bainite that forms above M_s and generates minimal transformation stresses by cooling slowly through the martensite region and forming low temperature isothermal bainite. The temperature of the isothermal hold determines the relative proportions of martensite and bainite.

Figure 3 shows the measured temperature-time path for a 120-mm cylinder after removal from the austenitization bath and immersion into the 482°F molten salt cooling bath. The actual bath differs from the ideal because of thermal lag due to the large mass of the block. Also shown is the slope giving the average cooling rate in the critical region of the CCT diagram. This average rate happens to approximately equal that required to just miss the bainite knee above M_s for the 3 percent composition. For this reason, the lower temperature of 392°F was selected as the isothermal hold temperature for this system to assure faster cooling so that the bainite knee above M_s is bypassed.

Tables 2, 3, and 4 give the mechanical properties for the 2 percent nickel composition at 482°F, the 3 percent nickel composition at 482°F, and the 3 percent nickel composition at 392°F isothermal holds, respectively.

Table 2. Mechanical Properties of ASTM A723 Steel Containing 2 Percent Nickel and Heat Treated With Isothermal Process at 482°F

Spec. No.	Tensile Test				Charpy Test (ft-lbs)				
	YS (Ksi)	UTS (Ksi)	RA (%)	EL (%)	-70°F	-40°F	-20°F	0°F	RT
1	176	191	38	13	-	13	-	-	-
2	173	193	35	11	-	13	-	-	-
3	173	190	33	10	-	10	-	-	-
4	173	189	40	12	-	9	-	-	-
5	158	164	21	8					
Aver	172	185	35	11	-	11	-	-	-

YS: Yield Strength, UTS: Ultimate Tensile Strength, RA: Reduction-in-Area, EL: Elongation, RT: Room Temperature

Table 3. Mechanical Properties of ASTM A723 Steel Containing 3 Percent Nickel and Heat Treated With Isothermal Process at 482°F

Spec. No.	Tensile Test				Charpy Test (ft-lbs)				
	YS (Ksi)	UTS (Ksi)	RA (%)	EL (%)	-70°F	-40°F	-20°F	0°F	RT
1	150	167	58	17	-	28	34	42	60
2	150	167	60	17	-	29	46	47	63
3	151	167	61	17					
4	150	167	57	16					
Aver	150	167	59	17	-	28	40	44	62

Table 4. Mechanical Properties of ASTM A723 Steel Containing 3 Percent Nickel and Heat Treated With Isothermal Process at 392°F

Spec. No.	Tensile Test				Charpy Test (ft-lbs)				
	YS (Ksi)	UTS (Ksi)	RA (%)	EL (%)	-70°F	-40°F	-20°F	0°F	RT
1	163	174	57	24	46	52	-	54	54
2	163	173	59	24	48	52	-	55	57
Aver	163	174	58	24	47	52	-	55	56

Figure 4 is a plot of the temperature dependence of the Charpy impact energies for the 100-pound blocks at the two isothermal temperatures. The mean values from Tables 2, 3, and 4 are plotted. Although only one data point was obtained for the 2 percent nickel specimen, the lowest ductile-brittle transition temperature is clearly indicated for 3 percent nickel with the 392°F isothermal hold.

DISCUSSION

The metallurgical goal of the present study is to develop a process for obtaining a mixed microstructure of low temperature martensite and isothermal bainite while avoiding formation of bainite above M_s. This can be achieved in components weighing on the order of 100 pounds by optimizing the combination of composition and isothermal quench-hold temperature.

The low Charpy values at -40°F for the 2 percent nickel specimen relative to the 3 percent sample processed at the 482°F isothermal hold temperature is attributed to the large difference in hardenability between the two compositions.

These values obtained for the 3 percent nickel are generally considered acceptable for components of this steel. The results for the 3 percent nickel specimen with the isothermal hold at 392°F are significantly better than the 482°F results and appear to be optimal for this steel since they are comparable to those obtained from small laboratory specimens (refs 1,2). The 392°F hold temperature provides a faster cooling rate with a microstructure that is evidently free of high temperature bainite. The added advantage of the lower isothermal hold temperature is a reduction in ductile-brittle transition temperature. The ductile-brittle transition temperature is inherently dependent on the isothermal hold temperature (ref 2).

The disadvantage of lower isothermal hold temperatures is that the relative amount of martensite increases as the hold temperature is lowered. Nonuniform martensite transformation (volume increase) due to nonuniform cooling of a component below M_s is the primary source of quenching stresses. Thus, for minimal residual stresses, one should minimize the cooling rate to minimize temperature differences within the component as martensite forms, and one should limit the total amount of martensite formed. These constraints place a lower limit on the isothermal hold temperature.

Current muzzle brake castings for the 155-mm are good candidates for isothermal processing because of their tendency to propagate pre-existing surface defects into cracks during conventional quenching. Their complex shapes may be a contributing factor. These castings actually weigh around 300 pounds; however, their surface-to-volume ratio is much larger than that of the cylinders used in the present experiments, so the cooling rates for the brakes are expected to be comparable despite the mass differences.

The focus of the present report is the application of isothermal processing to eliminate quench stresses and cracks in components that weight several hundred pounds or less. Another potentially important manufacturing application relates to improved fabricability of high hardness components such as firing pins, sleeves, and rollers. Because of the inherently low residual stresses accompanying isothermal transformations, such processing can be employed *after* machining to final form while the component is in a softened condition. This is not feasible with standard quench hardening because of severe component distortion generated by transformation stresses. Studies of this approach are in progress.

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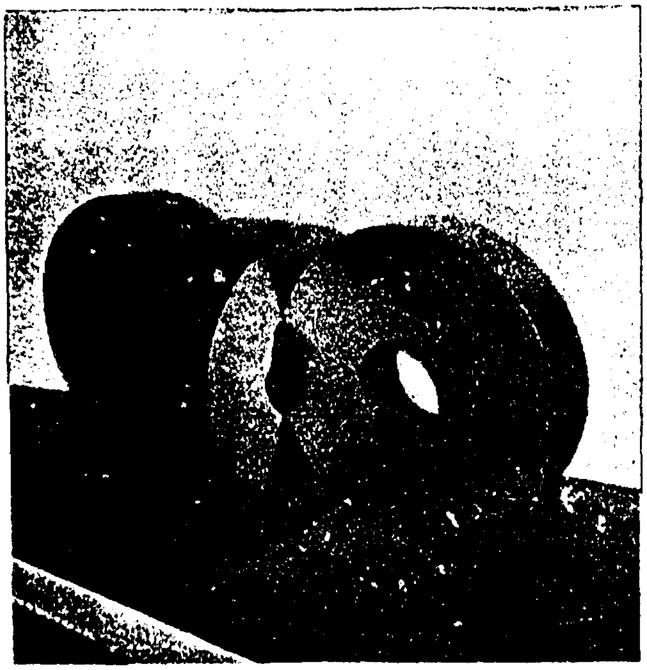

Figure 1. Photograph of typical cylinders used in the present study.

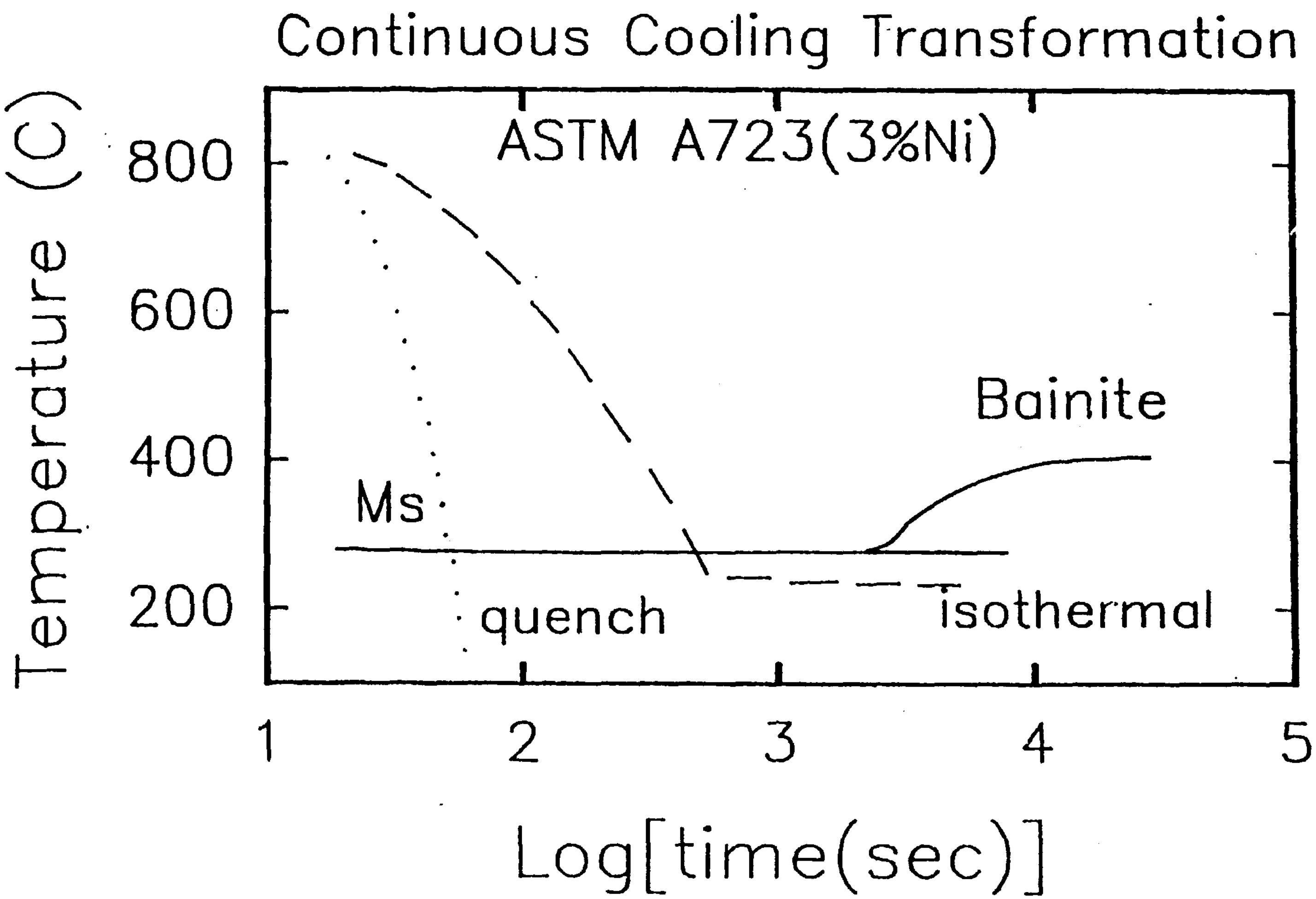

Figure 2. CCT diagram for ASTM A723 with 3 percent nickel. The standard quench cooling path that generates high quench stresses is indicated by the dotted line. The dashed line is a cooling path that bypasses the bainite knee above M_s, and produces lower residual stress in a component by cooling slowly through the martensite region and forming low temperature isothermal bainite.

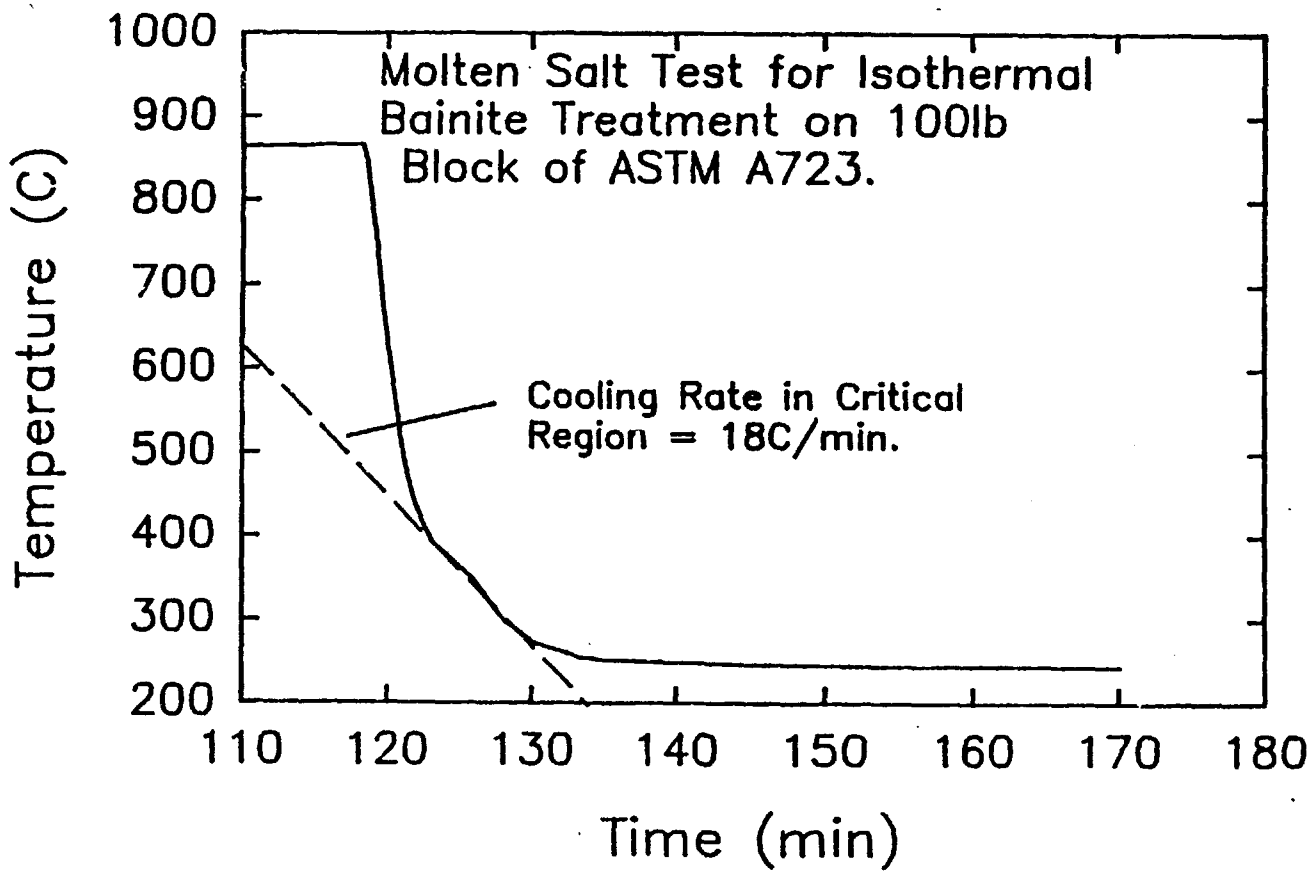

Figure 3. Measured cooling path for a 100-pound 120-mm cylinder after austenitizing and subsequent immersion in a molten salt bath maintained at 482°F (250°C).

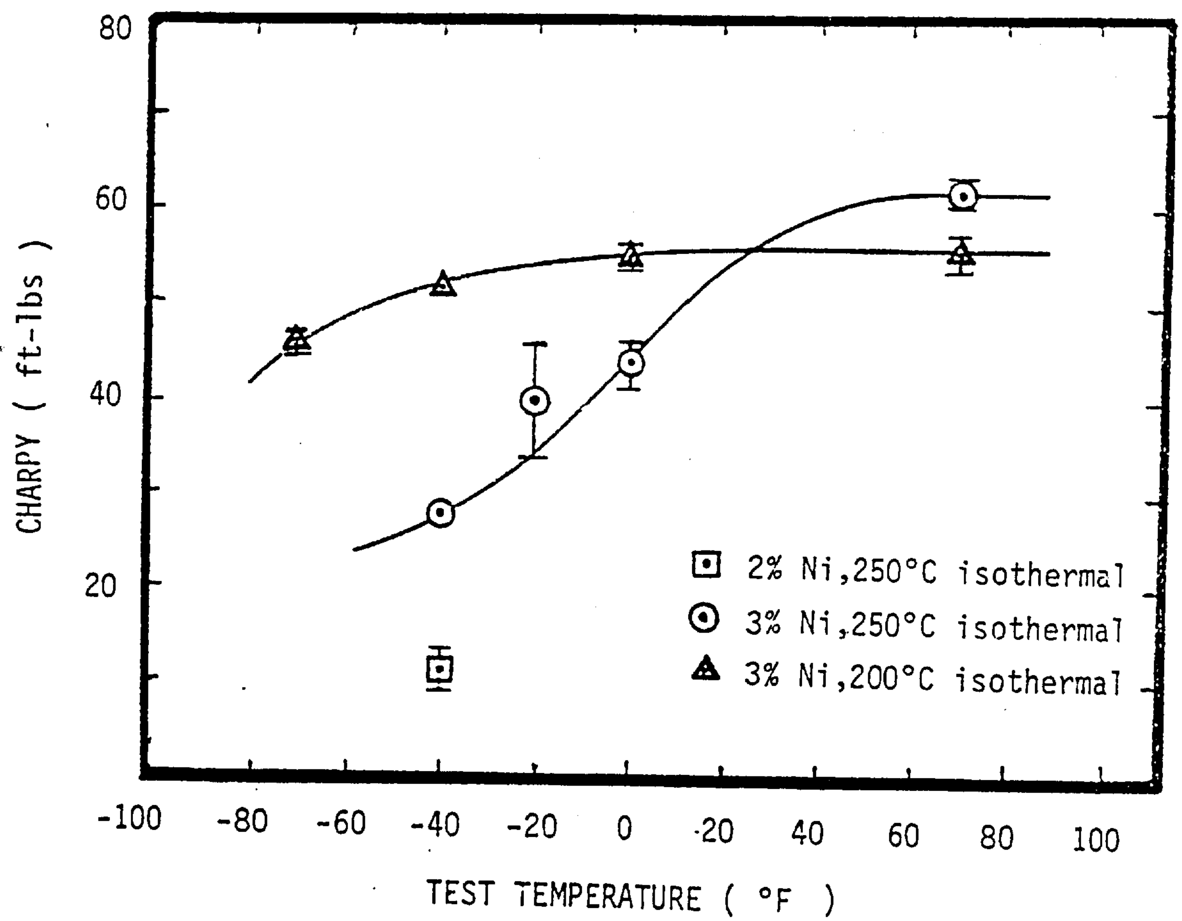

Figure 4. Temperature dependence of Charpy impact energy for specimens obtained from the midwall region of the three 100-pound cylinders.

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